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[illegible] TRANSIENT CONDITIONS

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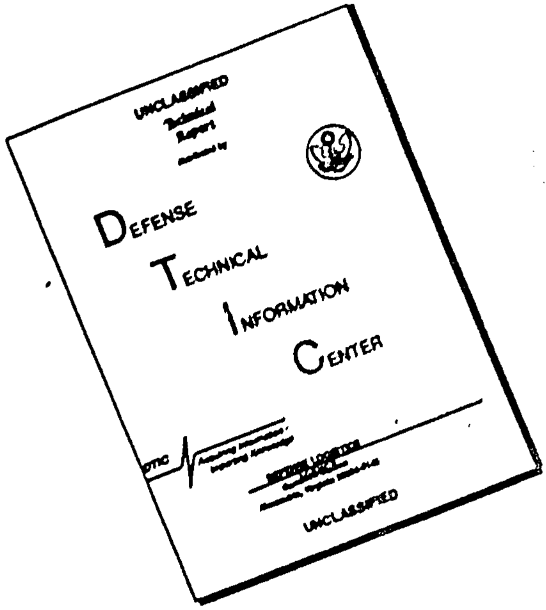

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TECHNICAL NOTE NO. 82-13

MEASUREMENT OF THE COMBINED HEAT AND WATER-VAPOUR FLOW THROUGH CLOTHING UNDER TRANSIENT CONDITIONS

by

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MARCH 1982
OTTAWA

ABSTRACT

A sweating hot plate for the study of combined heat and water-vapour flow through clothing under transient conditions is described. The results are in good agreement with the mathematical model reported in a previous paper for several model clothing systems. The heat loss through wool clothing was found to be smaller than that through similar polyester clothing during periods of sweating and larger during subsequent periods of drying, because of the effects of absorption of water vapour by hygroscopic materials. A comparison was made of the heat and vapour transmission of the clothing systems by incorporating a vapour-impermeable fabric or the waterproof but vapour-permeable fabric Gore-Tex. Liquid water was observed to condence on the inner surface of both fabrics during periods of sweating but the Gore-Tex dried within a few minutes of the end of the sweating period. Gore-Tex was found to be vapour permeable even at temperatures below 0°C when frost was forming on its inner surface.

RÉSUMÉ

Il s'agit ici d'une plaque chauffante suintante servant à étudier le flux combiné de la chaleur et de la vapeur d'eau à travers le tissu dans des ceux du modèle mathématique exposé dans un article précédent et concernant plusieurs types de tissus utilisés dans la confection des vêtements. La perte de chaleur pendant les périodes de suintement s'est avérée moins importante par le tissu de laine que par le tissu de polyester de même épaisseur, et plus importante pendant les périodes subséquentes de séchage, et ce, en raison de l'effet d'absoption de la vapeur d'eau par les tissus hygroscopiques. On a comparé le degré de dégagement de la chaleur et de la vapeur des divers types de tissus en y incluant un tissu imperméable à la vapeur ou le tissu Gore-Tex imperméable à l'eau mais perméable à la vapeur. On a pu observer que l'eau se condensait sur la face interne de ces deux tissus pendant les périodes de suintement, mais que le Gore-Tex séchait en quelques minutes une fois le suintement interrompu. On a également constaté que le tissu Gore-Tex était perméable à la vapeur même à des températures inférieures à 0°C, lorsque du givre se formait sur sa face interne.

INTRODUCTION

A previous technical note (1) described a numerical model of combined heat and water-vapour flow through clothing which takes into account variation in the flows with time due to variations in sweat production rate or in ambient conditions. This paper reports on experimental studies performed on a laboratory apparatus known as a "sweating hot plate" which is designed to simulate the body so that the physics of heat and vapour flow through clothing can be investigated under controlled laboratory conditions, and so test the predictions of the numerical model.

The kinds of situation that both the numerical and laboratory models are designed to study are those in which, during periods of sweating, water accumulates in the clothing, either condensed as free water or absorbed by hygroscopic fibres, and later evaporates during periods of reduced sweat rate. Both models yield as their primary result a rate of loss of heat from the plate (or skin) for a skin temperature that is fixed and a sweat rate that varies according to a predetermined pattern. No attempt has been made to simulate the thermo-regulatory response of the body to that heat loss rate which may be expected to cause a variation in skin temperature and sweat rate in an attempt to maintain a constant body temperature. Nor have all possible avenues of heat loss from the body been included in the models. Most importantly, heat and vapour flow by forced convention, due to the effects of wind and of body motion, have been excluded. Accordingly, the models are far from giving a complete picture of the heat loss from an active human subject but they yield more information than static measurements of heat and vapour resistance of clothing under steady-state conditions.

THE SWEATING HOT PLATE

Sweating hot plates constructed by other researchers (for example, Ref. 2) have been designed to make measurements of the heat resistance and the vapour resistance of single or multiple layers of clothing under constant conditions. Such plates are therefore operated in one of two modes; with the plate surface either completely dry or completely saturated with water.

Measurements are taken after a stabilizing period of several hours so there is no requirement for rapid switching from one mode to the other. What they do require is a precise measurement of heat loss from a uniformly heated and wetted area. Accordingly they are constructed from heavy sheets of copper covered with thick layers of wicking fabrics or sintered metal sheets.

The function of the sweating hot-plate described here is quite different. Measurements of steady-state thermal and vapour resistance are made on other pieces of apparatus. What is of interest here is the variation in heat loss with time with variation in a controlled sweat rate. The requirement is therefore for a plate which can be wetted quickly with a small quantity of water fed to the surface of the plate at a controlled rate and a temperature control and power measurement system that will respond to rapid changes in heat loss. The plate has therefore been kept small and light with only a thin layer of wicking material, at some expense in uniformity of heat and wetting.

The sweating hot plate and associated controlling hardware are shown schematically in Figures 1 and 2. The central portion of the plate is a 3-mm-thick aluminum disc with a area of 0.01 m^2. Around the inner plate is a guard ring of the same material and the same area separated by a 1-mm gap. Below these two plates is a 50-mm-thick layer of polyurethane foam insulation and a third aluminum plate (the base plate). The temperature of the inner plate is monitored by a thermistor and controlled to a preset value (usually 35°C) by heat applied through heating foils (3) attached to its lower side. The temperatures of the guard ring and of the base plate are measured relative to that of the inner plate by differential copper-constantan thermocouples and are controlled to give zero temperature difference. The heat loss from the inner plate downwards and sideways is therefore minimized and only heat loss upwards, through the clothing, is left. This heat loss is therefore equal to the power applied to the inner plate.

Water is fed to both the inner plate and the guard ring through 0.5-mm holes and spread by a thin sheet of paper (lens cleaning tissue) which is glued to the plates at the edges. There are four holes in each plate each connected by polyethylene tubing to a solenoid valve. Water is fed to each hole in turn from a syringe pump (4).

The sweating hot plate is mounted in a heated, insulated box with its top surface exposed through a hole in the lid. The box contains the syringe pump, solenoid valves and water supply and is in turn placed inside a controlled environment-chamber (5).

Measurement and control of temperatures, heater powers and water flows are performed by a Hewlett-Packard 1000 mini-computer interfaced to a HP 3455A digital voltmeter and HP 3495 scanner. During each cycle of the controlled program (usually every 20 seconds) the temperatures of the three plates are measured and current is applied to the three heaters, from voltage regulated power supplies, for a length of time calculated to keep the temperatures at the required values. The required power is calculated according to equation [1].

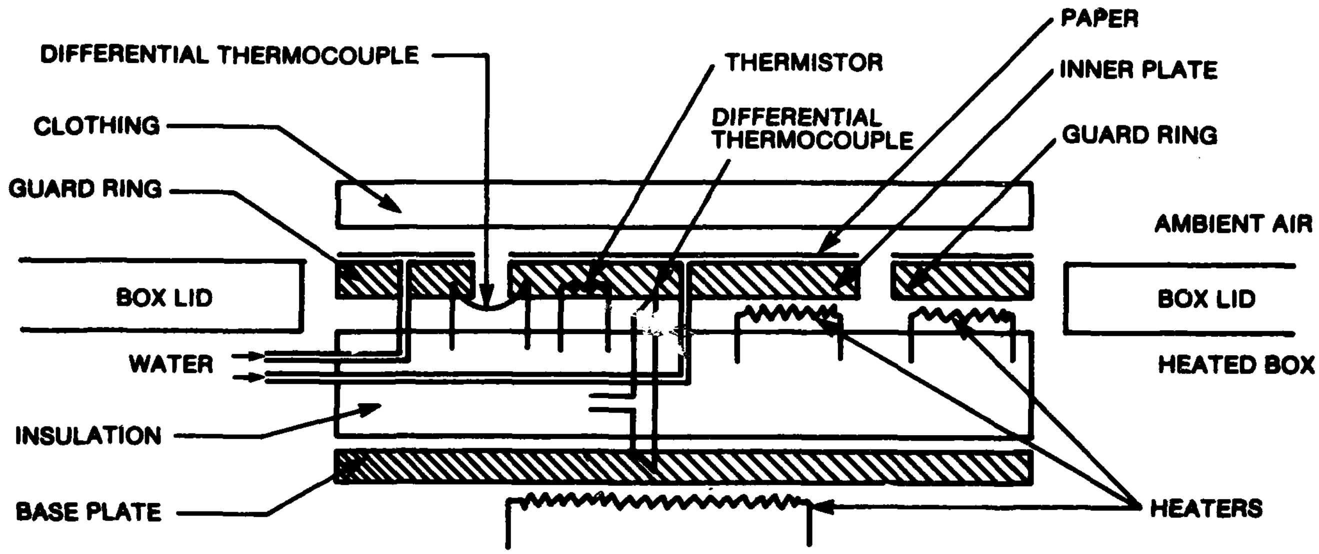

Fig. 1: Schematic diagram of the sweating hot plate. The heat required to keep the inner plate at a fixed temperature is monitored. The guard ring and base plate are kept at the same temperature as the inner plate to eliminate all but upwards heat loss. Water is feed at a controlled rate to the inner plate and guard ring and spread by a thin layer of paper.

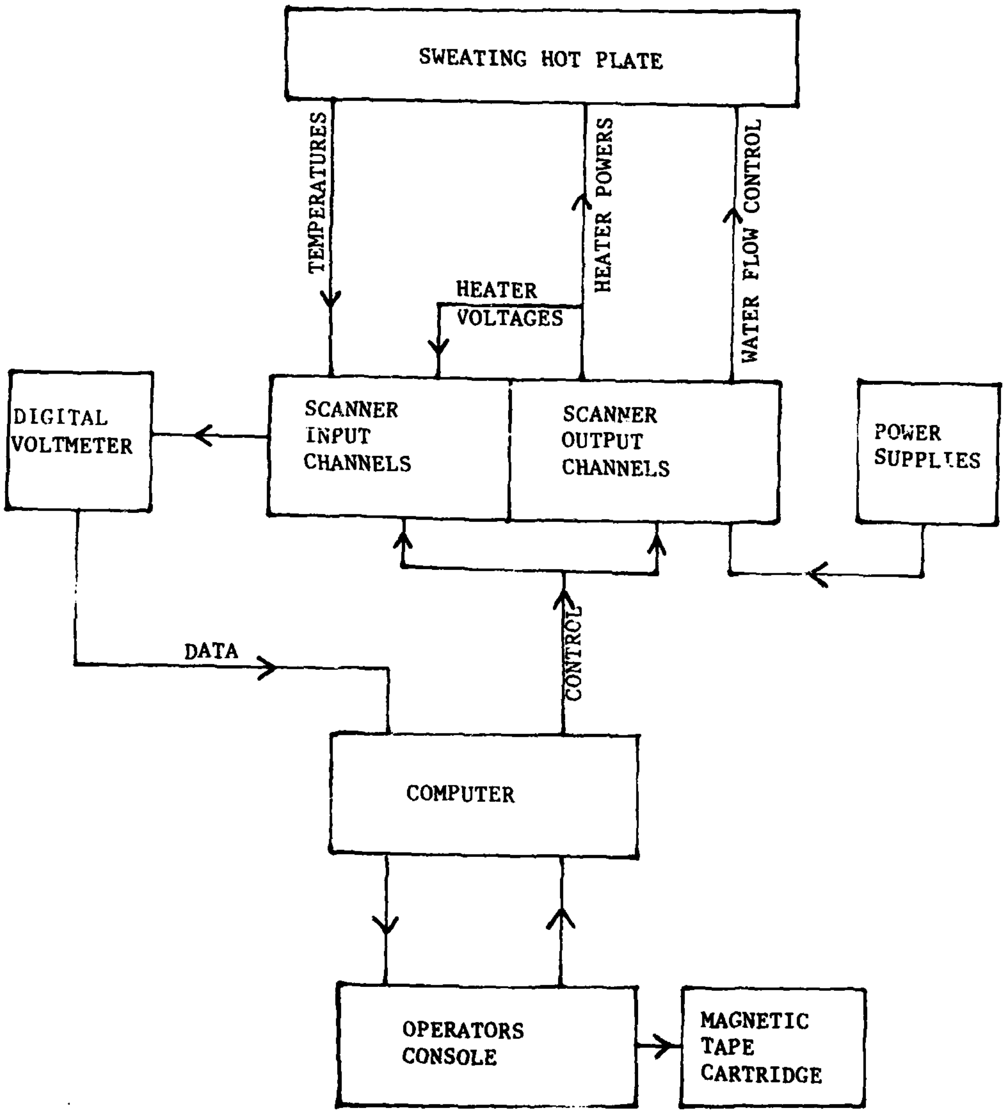

Fig. 2: Schematic of the sweating-hot-plate measurement and control system.

$$Q(t) = \frac{1}{\tau}\int_{0}^{t} Q(t')_{e}^{(t'-t)/\tau}dt' - g(T(t) - T_s) \qquad [1]$$

where $Q(t)$ is the power applied at time t.
$T(t)$ is the measured temperature.
T_s is the desired temperature.

The first term in equation [1] is an average over all past times with weighting given to more recent times according to the time constant τ. The second term is a correction which increases or decreases the power to be applied according to the distance the present temperature is from the set point with gain factor g.

The cycle time, the time constant and the gain are under operator control and are selected empirically to give a compromise between good temperature control and a noise-free $Q(t)$.

Typically with a 20-s cycle time, τ of 50 s and g of 5 W/K, temperatures can be controlled to ±0.01 K during periods of constant heat loss with deviations of 0.1 K lasting 200 s when the heat loss changes abruptly by a factor of 2 at the onset of sweating. The noise on $Q(t)$ is a few percent.

The computer records the temperature and power applied to each plate during each cycle on magnetic tape cartridges and also records the ambient air temperature and temperatures within the clothing layers which are measured relative to temperature of the inner plate with differential thermocouples.

Control of the water flow is independent of the temperature and power control. The computer switches the syringe pump on and off at operator request and automatically cycles through the eight water feed lines. The flow rate is set manually by potentiometers that regulate the speed of the syringe pump motors. These are located outside the environmental chamber.

RESULTS

EFFECTS DUE TO HYGROSCOPIC MATERIALS

The previous paper (1) reported predictions by the numerical model of the difference in heat flow through clothing made of hygroscopic and non-hygroscopic materials during and after a period of sweating at a constant rate. To test these predictions, experiments were performed on several

layers of either wool or polyester knit fabrics chosen to have, as closely as possible, the same total mass, thickness, heat resistance and vapour resistance. The two materials, therefore, differ substantially only in their regain values. These values are shown in Table I.

In the experiments the plate was maintained at a temperature of 35°C in an atmosphere of 21°C and 30% relative humidity. After an initial stabilization period with no water flow the sweat was switched on for a period of 1 hour at a rate of 0.83×10^{-4} kg/s m^2. This corresponds to a sweat rate from the whole body of 0.6 kg/h which is quite profuse. During this time, and for an additional hour after the cessation of sweating, the heat loss from the plate and the temperature at the centre of the clothing layers were monitored. These data are shown in Figures 3 to 6.

In the case of the polyester clothing, the heat loss (Figure 3) rose fairly rapidly to a roughly steady value of 150 to 160 W/m^2. The fluctuations in this value may be attributed to variations in the temperature and humidity of the laboratory environment which were not controlled. The rise time is governed by the rate at which the water spreads over the surface of the plate. It takes a finite mass of water to saturate the paper wicking layer completely. Until this mass of water has accumulated at the plate surface, only part of the surface is wet and contributing to the evaporative heat loss. This effect is taken into account in the numerical model by the presence of a "plate vapour capacity" (see Ref. 1) the value of which (1.7×10^{-6} kg/m^2 Pa) has been chosen to give the correct rise time in the heat loss.

The predictions of the numerical model agree well with the observed heat loss rate except during the period of about 300 s immediately after the cessation of sweating. During the period of sweating, water has been fed to the plate at a rate slightly higher than that at which it can diffuse out from the clothing. According to the theory this excess water should condense within the clothing layers. Thus when the water flow is switched off the plate should dry very quickly but the clothing will remain wet for about 200 s and the heat loss will fall to a new steady value, which is less than that with a wet plate but still larger than that with both plate and clothing dry, until all the water within the clothing has evaporated. What was observed experimentally was that the excess water remained at the plate so that the heat loss remained at the wet plate value for an extra 200 s until the water had evaporated. This disagreement is probably due to slightly erroneous values of water vapour resistance used in the calculation.

The variations of the temperature within the polyester layers is shown in Figure 4. At the onset of sweating there is a brief 1°C rise in clothing temperature that is due to absorption of water vapour by the slightly hygroscopic polyester fibres. At the cessation of sweating there is a corresponding drop in the clothing temperature as the absorbed water is evaporated. These temperature changes are predicted quite accurately by the calculation except at the end of the sweating period where the observed temperature drop is delayed by about 200 s. This is again due to the excess water being accumulated at the plate instead of within the clothing as predicted by the calculations.

TABLE I

Material	Thickness (mm)	Mass kg/m^2	Regain @ 65% RH (%)	Thermal Resistance m^2 K/W	Vapour Resistance m^2 Pa s/kg	Specific Heat j/kg K
(a) Air	1	-	-	0.032	5.6×10^6	-
Polyester Knit (6 layers)	2.88	0.767	1.5	0.058	4.2×10^7	1000
Wool Knit (4 layers)	2.76	0.716	12.6	0.058	4.2×10^7	1300
Air	10	-	-	0.12	5.6×10^7	-
(b) Air	5.0	-	-	0.087	2.8×10^7	-
Goretex	0.3	0.169	4.5	0.003	2.2×10^7	0.35
Coated Fabric	0.3	0.169	4.5	0.003	10^{12}	0.35
Air	4.4	-	-	0.082	2.5×10^7	-

Material properties used in the numerical model:
(a) in the comparison of polyester and wool knits, and
(b) in the comparison of GoreTex and impermeable waterproof.
The thickness of the outermost adhering air layer has been estimated from the measured dry heat loss rates.

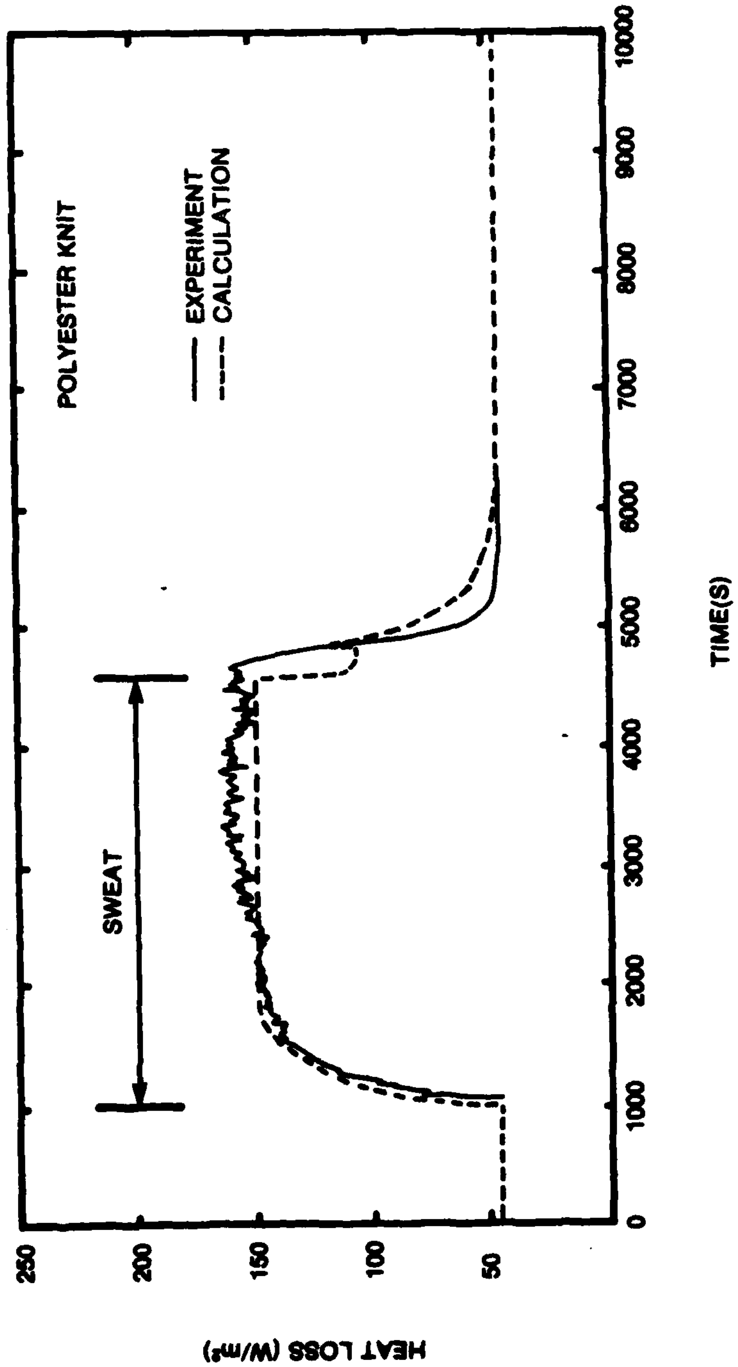

Fig. 3: Heat loss through polyester knit fabric. Water was applied at a rate of 8.3×10^{-5} kg/s m^2 for a period of 1 hour.

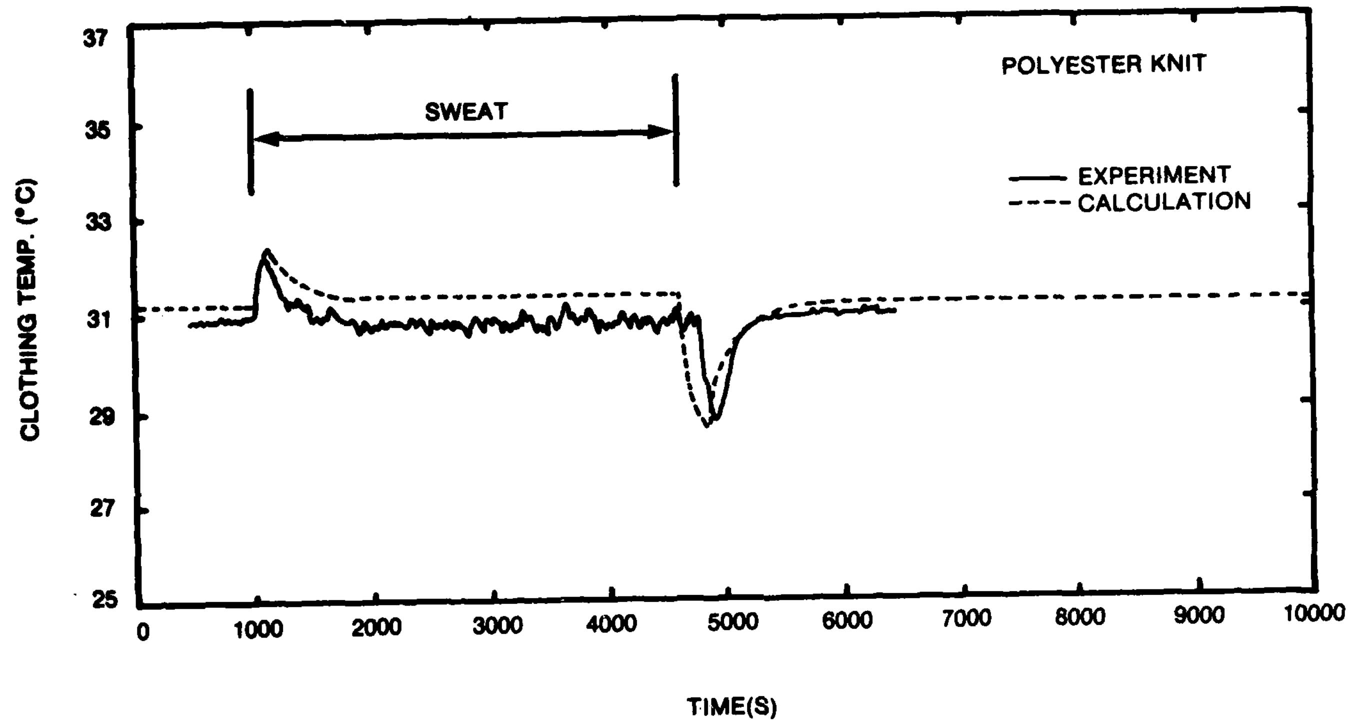

Fig. 4: The temperature of the centre of the polyester knit. The plate and ambient air temperatures were 35 and 21°C respectively. The rise in temperature at start and the fall at the end of the period of sweating are due to absorption and subsequent desorption of water vapour by the slightly hygroscopic fibres.

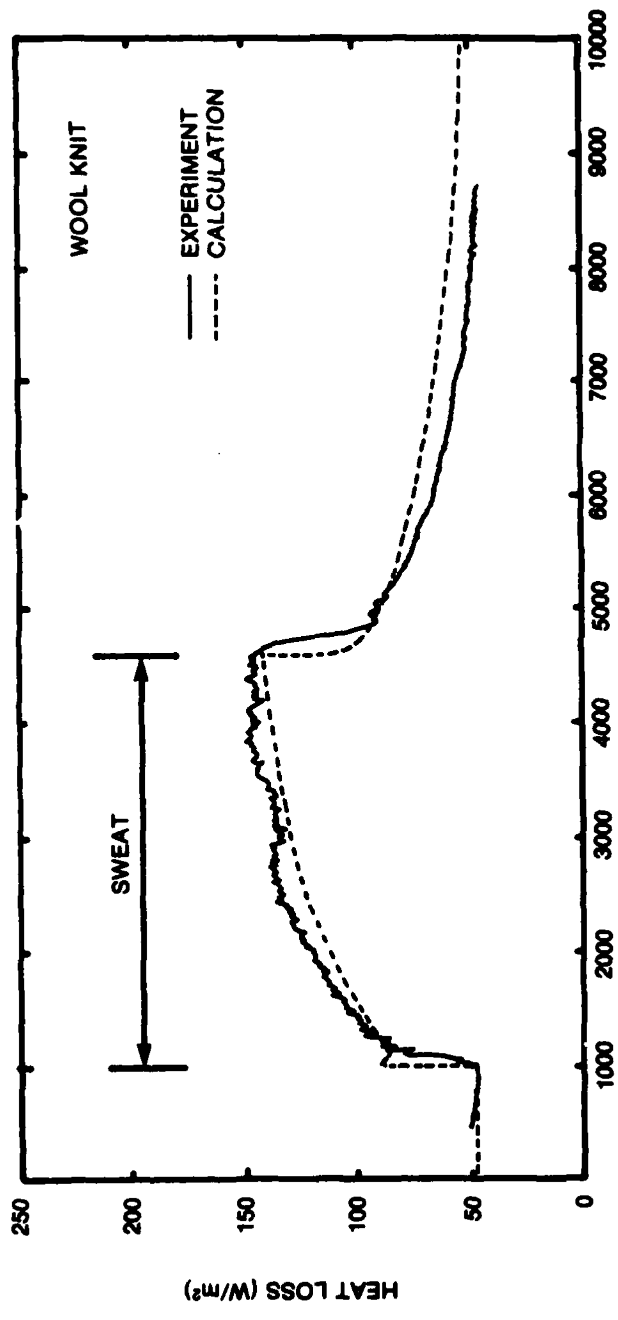

Fig. 5: Heat loss through wool knit. The rise in heat loss during the period of sweating and the subsequent fall are much slower than for the similar polyester fabric under the same conditions.

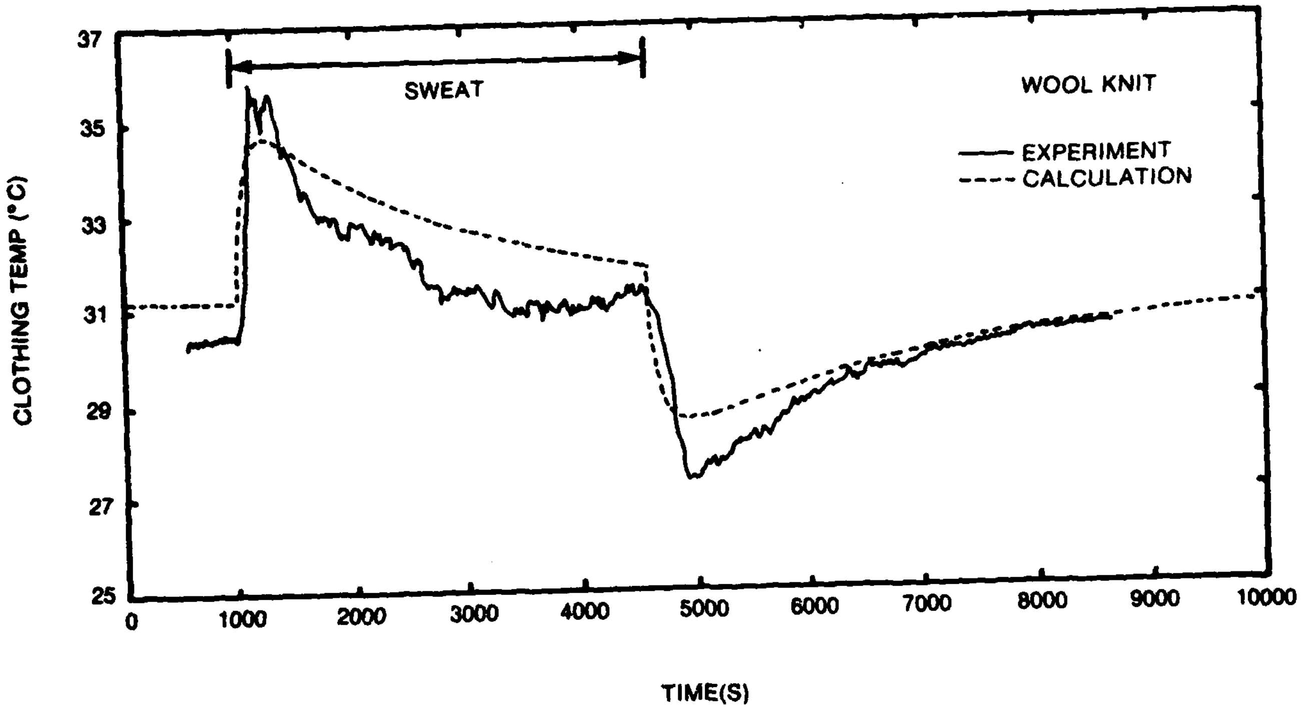

Fig. 6: The temperature of the centre of the wool knit fabric. The changes in temperature are much larger and of longer duration than for polyester due to the much higher hygroscopicity of wool.

In the case of wool clothing, the rise in heat loss (Figure 5) was much slower than for polyester and was still rising even at the end of the period of sweating. Correspondingly, the return to the dry heat loss rate after the period of sweating was also slow. The temperature changes (Figure 6) due to the absorption and subsequent desorption of water vapour by the highly hygroscopic wool fibres are much greater than in the case of polyester. The temperature of the wool clothing is observed to rise, briefly, above the plate temperature so that for a short time the sensible heat flow is reversed and the plate gains heat from the clothing.

The agreement between theory and experiment here is quite good except that the changes are observed to be somewhat faster than predicted by the theory. The basic prediction of the theory, that the effect of highly hygroscopic clothing is to reduce heat loss during periods of physical activity accompanied by sweating and to increase heat loss during subsequent sedentary periods with little sweating, is vindicated by the experiment. The actual difference in heat loss over the one hour sweating period is not large, being about 80 kJ/m^2, or an average difference in heat loss of 23 W/m^2. This is sufficient to cause a difference in mean body temperature at the end of the hour of about 0.3°C which should be observable in a physiological trial but is not of great physiological significance. However, the additional heat stress imposed on the wearer of the wool clothing might well result in a higher sweat rate which would exacerbate the additional heat loss after sweating ceases thus increasing the severity of "post-exercise chill".

EFFECTS DUE TO CONDENSATION WITHIN THE CLOTHING

Even if the clothing materials are of very low hygroscopicity, it is possible for water to accumulate within the clothing if the vapour pressure at any point rises to the saturation vapour pressure at the local temperature. This is certain to occur if the clothing contains a layer of highly impermeable fabric and is quite probable if the ambient temperature is low since the saturation vapour pressure decreases dramatically with reduced temperature. There is currently much interest in the accumulation of sweat in military clothing, prompted largely by the appearance on the market of the material Gore-Tex which was developed to alleviate the problem in many applications.

Gore-Tex is a microporous film of Teflon (polytetrafluoroethylene) laminated between two layers of textile fabric to give a material which is impermeable to liquid water and forced air currents but is highly permeable to diffusion of water vapour. Thus it may be expected that a layer of Gore-Tex used as the outermost fabric layer of a garment will be waterproof but "breathable". That is, that it will allow the escape of water vapour from sweat, preventing accumulation of water within the clothing. Gore-Tex is therefore an attractive candidate for application in rainwear but some question remains as to whether it can be expected to be of value in clothing designed for low-temperature use where frost may be expected to form on the inside surface of the Gore-Tex laminate, possibly plugging the pores and preventing escape of water vapour.

Two sets of experiments were performed to compare the heat and vapour loss through Gore-Tex to that through a layer of totally impermeable waterproof fabric. One was at room temperature with no clothing layer except the Gore-Tex or the waterproof fabric. Under these conditions the difference may be expected to be greatest. The other set was conducted at low temperature using an additional insulating layer of batting. Here it may be expected that the differences will be minimal and that any problem with frosting will be manifest.

The room temperature results are shown in Figures 7 to 10. Here the sample was held at a distance of 5 mm above the plate with a plate temperature of 35°C and an ambient atmosphere of 23°C and 30% RH. A sweat rate of 0.82×10^{-4} kg/m^{2}s was applied for 2000 s. The properties of the samples, and the air layers, are listed in Table I.

Figure 7 shows the heat loss through a Gore-Tex sample. The observed pattern of heat loss is close to the theoretical predictions although there is some quantitative discrepancy. At the onset of sweating the heat loss rises quite quickly to a region of more gentle rises which is predicted to be flat. After the sweat stops the heat loss remains high, due to the evaporation of water that has accumulated on the plate, for a few hundred seconds and then falls to a new value while water that condensed on the inside surface of the Gore-Tex evaporates.

The corresponding curve of the temperature of the Gore-Tex is shown in Figure 8. At the onset of sweating, there is a peak in the Gore-Tex temperature as hygroscopic absorption of water by the nylon layers of the laminate takes place followed by a return to a value close to, but above, the value during dry heat loss. This is due to water condensing on the Gore-Tex and liberating heat. When the sweat has been switched off and the plate has dried there is a drop in temperature while the water that has condensed on the Gore-Tex, or has been absorbed by the nylon, evaporates.

There are two effects to which the discrepancies between theory and experiment may be attributed. One is that the nylon of the Gore-Tex laminate is observed to expand as it gets wet so that the fabric wrinkles and the thicknesses of the airlayers change. The other is that the uneven wetting of the plate causes the temperature of the plate to vary from place to place. This promotes convection currents that carry both heat and vapour. Neither of these effects can be readily included in the theory.

For comparison, a similar experiment was performed with a waterproof polyurethane-coated nylon in place of the Gore-Tex. The heat-loss data are shown in Figure 9 and the temperature at the nylon fabric in Figure 10. When the sweat is switched on, some of the water evaporates from the plate and travels to the waterproof where it condenses. No water vapour can escape from the system. This water vapour carries with it about 50 W/m^2 of heat from the plate to be liberated at the waterproof, raising its temperature by 2°C. Since the rate of diffusion is less than the sweat rate, water accumulates at the plate and the heat loss remains high for a considerable length of time after the water flow is switched off until all the water fed to the plate has collected at the waterproof, at which point the heat loss returns to its dry value.

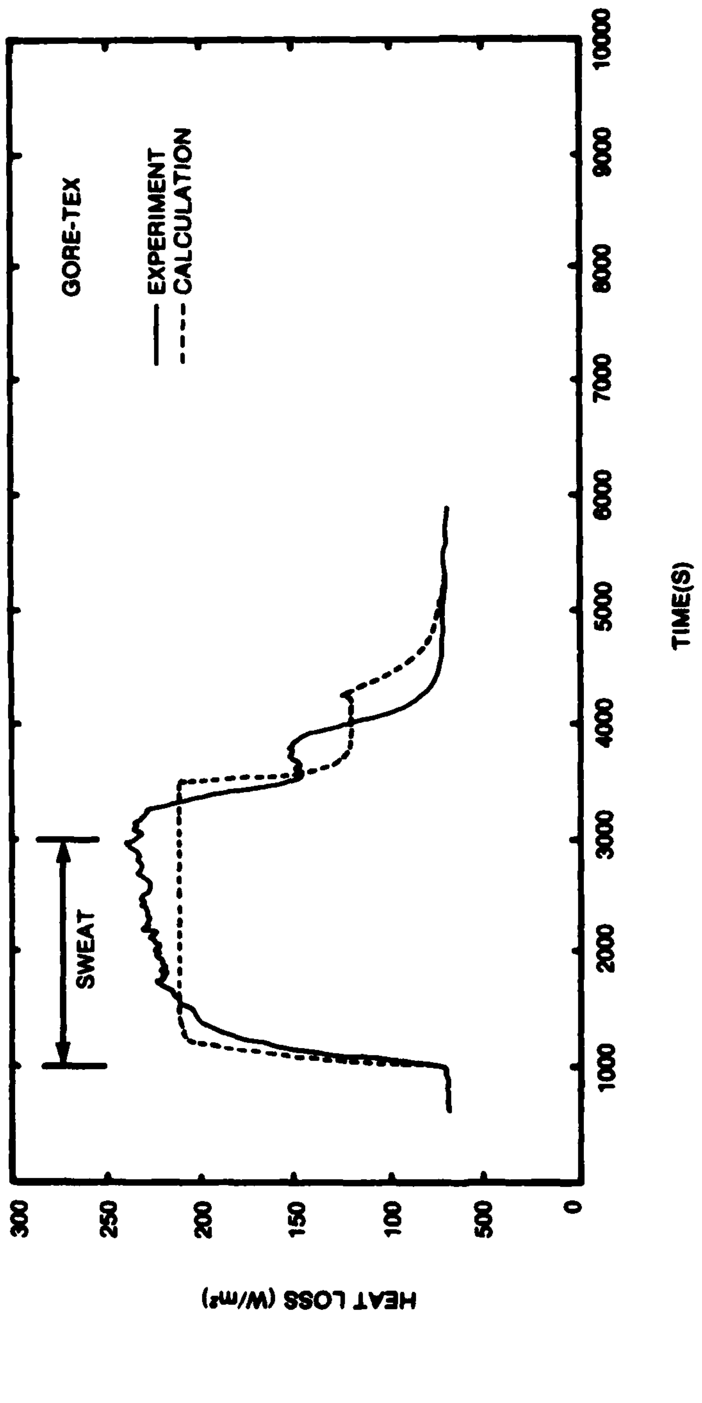

Fig. 7: Heat loss through a layer of Gore-Tex at 23°C ambient air temperature. Some water vapour condenses on the Gore-Tex during the period of sweating and evaporates after the sweat is switched off causing the heat loss to remain at a level intermediate between the dry and wet heat loss rates for a few minutes.

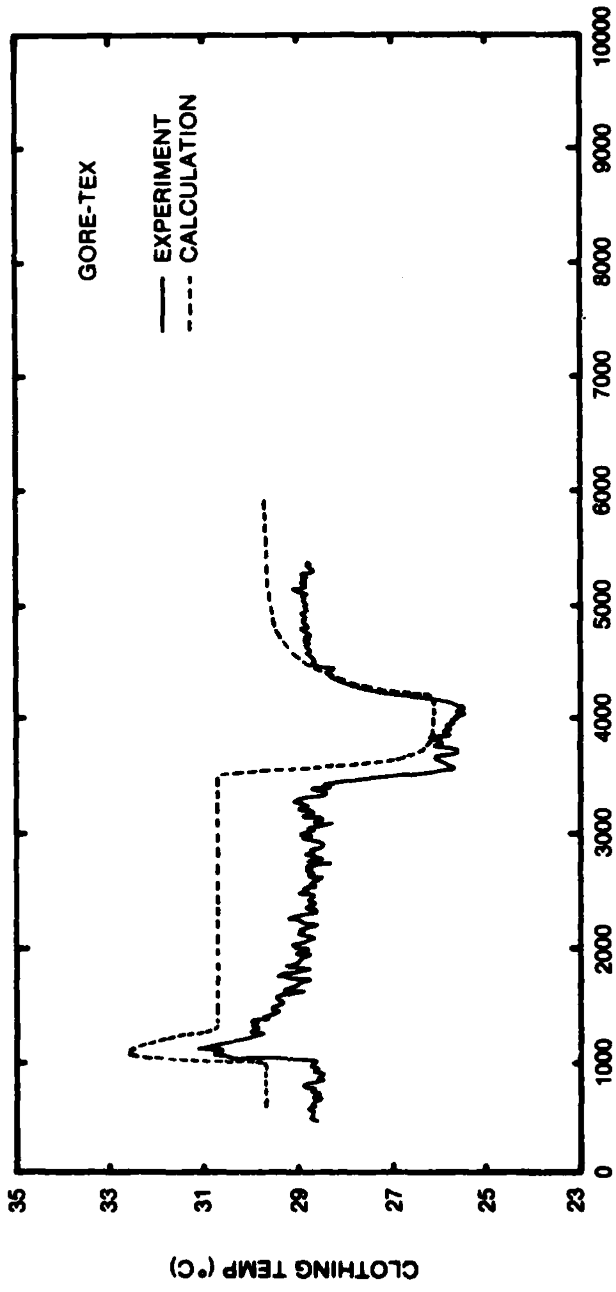

Fig. 8: Temperature of the Gore-Tex fabric. The initial peak is due to hygroscopic absorption by the nylon layers of the Gore-Tex laminate. The much larger dip in temperature at the end of the sweating period is due to the evaporation of water that has condensed on the Gore-Tex.

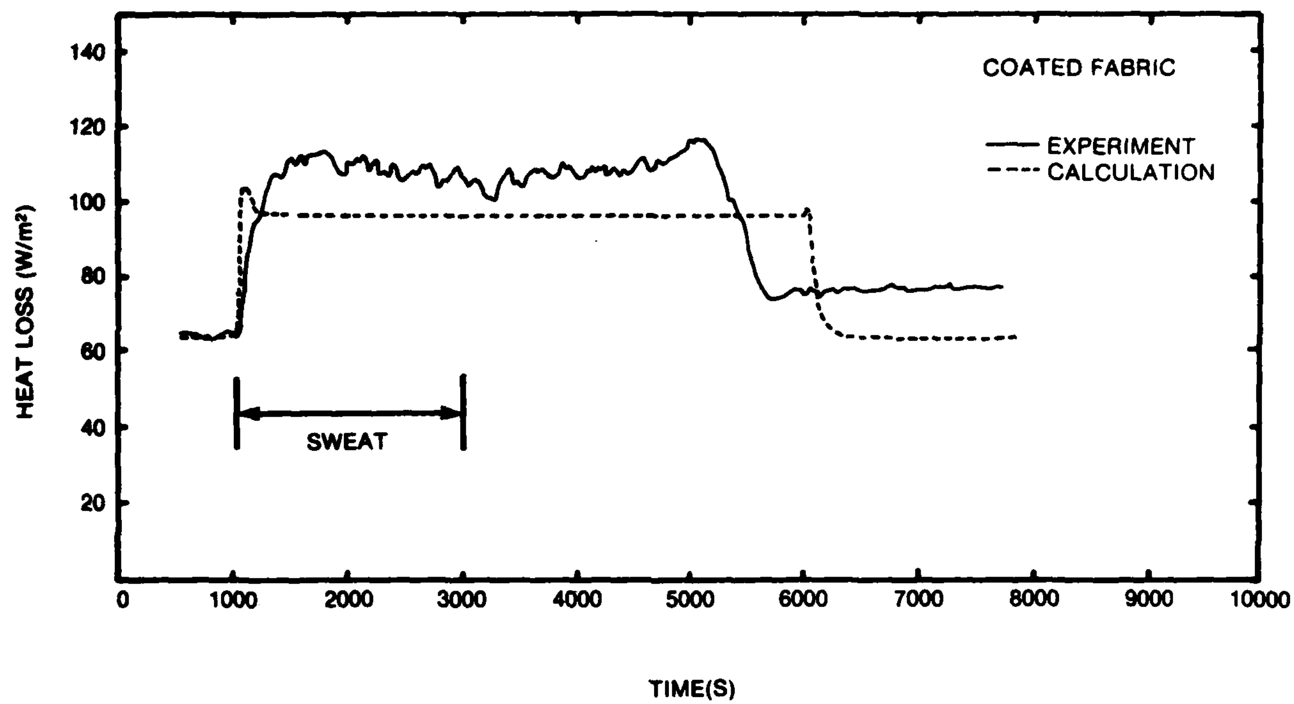

Fig. 9: Heat loss through a layer of impermeable polyurethane-coated nylon. Water evaporates from the plate and condenses on the nylon but at a much lower rate than that at which it is fed to the plate. The heat loss remains high, therefore, after the sweating ceases until all the water condenses on the nylon.

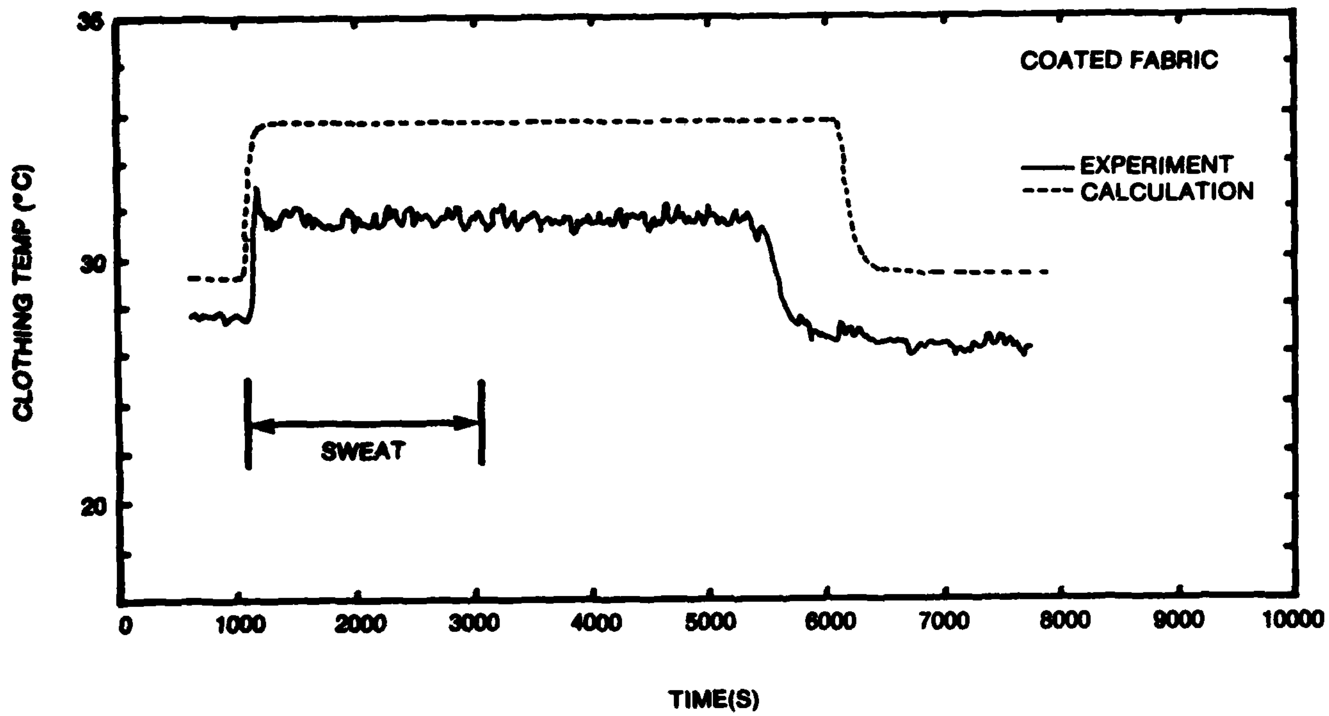

Fig. 10: Temperature of the impermeable fabric. Condensation of water on the fabric raises its temperature above its value during dry heat loss.

Again there is considerable numerical disagreement between the theory and experiment but it should be noted that the error is less than that which would result from a simple overall vapour resistance model of the vapour flow. Since the total vapour resistance of the air layers plus the coated fabric is very large, the vapour loss through the whole system is zero. Hence a simple overall vapour resistance model would predict zero extra heat loss due to sweating. Both the experiment and the more sophisticated theory give some extra heat flow, although it is only about one third the extra heat loss observed with Gore-Tex. These experiments and calculations exhibit the considerable advantages to be gained from a Gore-Tex rather than an impermeable rainsuit worn over little or no extra clothing. With Gore-Tex, the heat loss rises to a higher value during periods of sweating than the coated fabric and returns to its initial dry value more rapidly when sweating ceases. Although the clothing under the Gore-Tex may still become wet due to condensation of sweat, it will dry within a few minutes. It should be noted, however that the conditions under which these experiments were performed approximate those to be encountered on a dry spring day. The advantages of a Gore-Tex rainsuit are less apparent under more humid conditions. The dependence of the steady state heat loss on varying atmospheric conditions has been discussed in a previous paper (6).

To test the performance of Gore-Tex at low temperatures a second set of experiments were performed in the environmental chamber at a temperature of -17°C. The humidity was not controlled but since even saturated air at this temperature contains very little moisture, the effect of relative humidity of the environment is negligible. A 6-mm layer of synthetic fibre batting (Thinsulate C 150) was placed between the plate and the Gore-Tex primarily to ensure that the temperature at the Gore-Tex would be below 0°C but also to simulate, if crudely, a cold-weather garment. (A more realistic simulation of cold-weather clothing would have required the addition of many layers of fabric making the data much more difficult to interpret.) The relevant properties of the clothing layers are listed in Table I.

The heat-loss curves for both the Gore-Tex and the coated fabric are shown in Figure 11. The experimental curves are identical within experimental error for a period of 10,000 s. The calculations also predict identical heat-loss rates. The heat loss during sweating was predicted quite accurately by the calculation; the small discrepancy is within the error to be expected due to uncertainties in the water-vapour resistances assumed. At the end of the sweating period the heat loss dropped immediately indicating little or no accumulation of water at the plate. The return to the dry heat loss rate, however, was much slower than predicted. The step-wise drop in the calculated curve is due to the representation of the batting by discrete points rather than as a continuum. The calculation predicts water condensation at each point and a plateau in the heat loss curve during the time that each point in turn (the innermost first) takes to dry. It is more realistic to assume that water vapour will condense over a continuous region of the batting and that the drying process will be continuous. This is not, however, the most important discrepancy. The calculation predicts a return to the dry heat loss rate within about 3 hours. In the case of Gore-Tex the time involved was about 10 hours and in the case of the coated fabric the return did not occur even after 10 hours. These observations may be attributed to the reduced thermal resistance of the water- or ice-impregnated batting. This effect is not taken into account in the theory. On

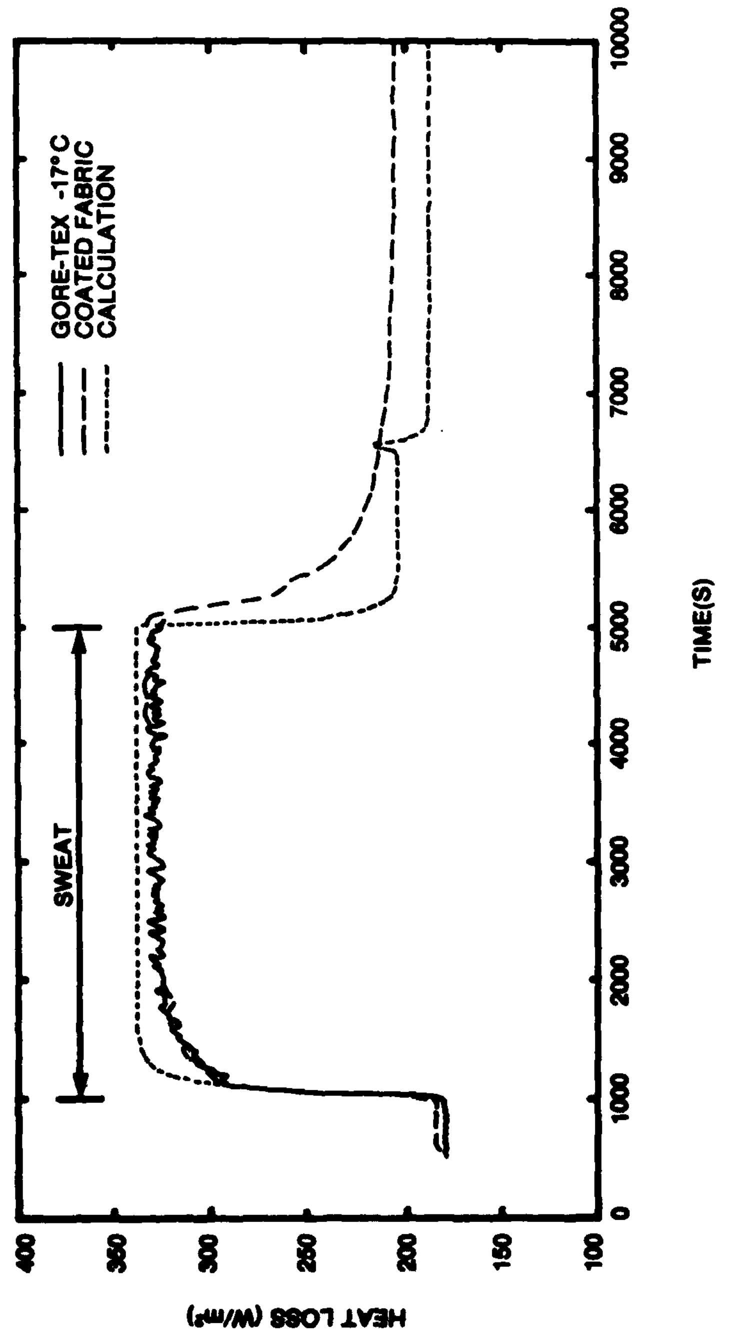

Fig. 11: Heat loss through Gore-Tex and impermeable fabrics at an ambient air temperature of -17°C. The heat loss after the sweating period remains higher than the dry value due to the accumulation of ice.

examination at the end of the experiment the coated fabric and the batting were fused together by about a 2-mm-thick layer of ice. With the Gore-Tex in place, only a few thin patches of ice were evident (only a few g/m^2 compared to a total water input of 330 g/m^2).

The prediction of the water accumulation within the clothing is shown in Figure 12. Since the water cannot escape through the waterproof, the mass gain increases linearly during the sweating period and remains constant thereafter. Some vapour can, however, escape through the Gore-Tex so the mass gain is somewhat less and then decreases slowly after the sweating ceases. These predictions are consistent with the observation that the heat loss rate returns to its dry value in 10 hours in one case and never in the other.

From the experiments and calculations it is evident that Gore-Tex is vapour permeable even at temperatures below 0°C and will permit clothing to slowly dry at these temperatures. The Gore-Tex does not, however, prevent the accumulation of water in the clothing, in the short term. The differences in heat-loss rates during sweating between a cold-weather garment made with Gore-Tex and one made with an impermeable outer layer are therefore negligible.

There are two materials manufactured as Gore-Tex. Type I is simply a layer of microporous Teflon whereas Type II has an additional layer of a hydrophylic polymer that is impermeable to organic liquids. The experiments described above were with a Type I material. Similar experiments were performed with a layer of Type II material without any nylon layers and yielded substantially the same results. There is no evidence of the water-vapour permeability of either material being degraded by frost.

CONCLUSIONS

In the two sets of experiments performed, one involving water-vapour absorption by hygroscopic clothing material, the other involving condensation within the clothing, the predictions of the numerical model were largely confirmed. The effect of a hygroscopic material was to keep heat loss low during a period of active sweating but high during the following period of no sweat production. When the clothing included a totally or partly vapour-impermeable layer, water was observed to evaporate at the plate and condense on the impermeable layer, increasing the heat loss above its dry value but keeping it smaller than would be the case with no vapour barrier present.

The waterproof but vapour-permeable fabric Gore-Tex was found to be vapour permeable even at temperatures below 0°C when frost was forming on its inner surface. However, the rate of diffusion of water vapour through the fabric under these conditions was low due to the small vapour pressure

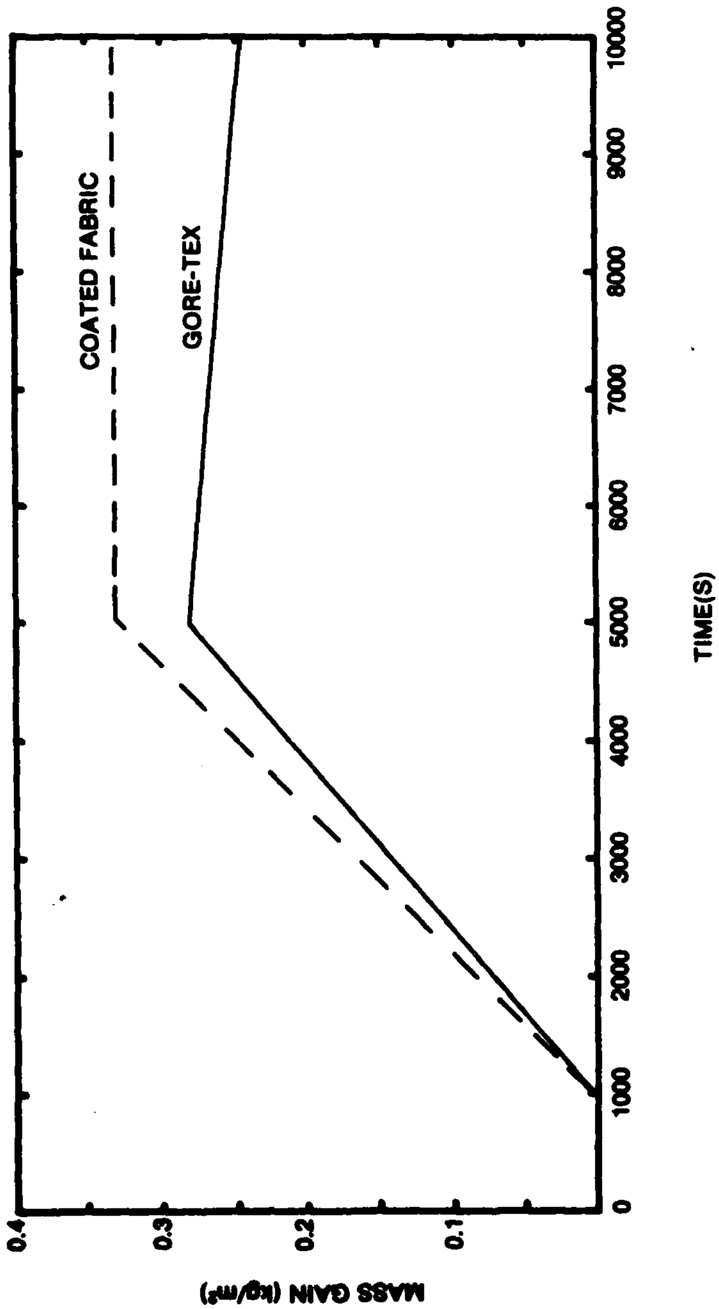

Fig. 12: Calculation of water accumulation within clothing at -17°C. Some escape of water vapour through the Gore-Tex is predicted.

gradient present at low temperatures. The use of Gore-Tex in clothing cannot be expected to prevent the condensation of water within the clothing but will permit the clothing to dry, quickly or slowly depending on the atmospheric conditions, when active sweating ceases.

Some quantitative discrepancies between theory and experiment were observed. These were attributed to: convective heat and vapour transport across airgaps induced by uneven wetting of the plate surface; changes in mechanical properties of nylon fabrics with the absorption of water; and changes in thermal resistance of battings with the accumulation of liquid water or ice. These discrepancies were not large, however, and should have little effect on the reliability of predictions, based on the numerical and laboratory models, as to the effectiveness of an experimental clothing system when worn by a live subject. Both models neglect additional heat transfer mechanisms and thermoregulatory mechanisms that will be operative on a live subject. Thus discrepancies between both models and physiological trials can be expected to be larger than discrepancies between the two models. Nonetheless, the models do point out differences in the heat and vapour transport characteristics of clothing systems involving different constituent materials and the conclusions drawn from the modeling work may be extrapolated to physiological trials if it is ensured that the conditions during the physiological trials are comparable to those used in the models.

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A sweating hot plate for the study of combined heat and water-vapour flow through clothing under transient conditions is described. The results are in good agreement with the mathematical model reported in a previous paper for several model clothing systems. The heat loss through wool clothing was found to be smaller than that through similar polyester clothing during periods of sweating and larger during subsequent periods of drying, because of the effects of absorption of water vapour by hygroscopic materials. A comparison was made of the heat and vapour transmission of the clothing systems by incorporating a vapour-impermeable fabric or the waterproof but vapour-permeable fabric Gore-Tex. Liquid water was observed to condense on the inner surface of both fabrics during periods of sweating but the Gore-Tex dried within a few minutes of the end of the sweating period. Gore-Tex was found to be vapour permeable even at temperatures below 0°C when frost was forming on its inner surface.

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